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RESEARCH MEMORANDUM

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By E. R. G. Eckert, Martin R. Kinsler
and Reeves P. Cochran

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SUMMARY

An investigation was made to determine the properties of wire cloth as a porous material for transpiration-cooled walls where a coolant is forced through the porous material to form an insulating layer of fluid on the heated surface of the wall. Materials presently available for transpiration cooling, such as sintered porous metals, do not have sufficient strength for applications in which the operating stresses are high. For applications where the stresses act primarily in one direction, a porous material with high strength in that direction is desirable. An example of such an application is in turbine-rotor blades where the centrifugal stress predominates. The suitability of a corduroy-type wire cloth manufactured from AISI type 304 stainless steel was investigated for this purpose.

The cloth was woven with considerably more wires in one direction than in the other. As woven, the cloth was too permeable for most transpiration-cooling applications, but by cold-rolling a porous material may be obtained with a wide range of permeabilities, which should cover most requirements for transpiration-cooled walls. The stiffness of the wire cloth could be increased by a brazing process that bonded the wires together. In order to provide an adequate basis for comparison of various porous materials, a reduced tensile strength was introduced for aircraft applications where strength-density ratio is important. The reduced tensile strength of the cloth after brazing and rolling was as high as 130,000 pounds per square inch, which is 2 to 3 times the ultimate comparable strength of compacted sintered metals. Spot-welding was found to be a satisfactory method of attaching wire cloth to solid structures and seam brazing afforded a means of attaching layers of cloth to each other.

INTRODUCTION

Transpiration cooling has been shown to be an effective means for cooling structures in high-temperature high-velocity gas streams (reference 1). In the transpiration-cooling process, the walls of the structure are made of a porous material and a coolant is forced through the porous wall to form an insulating layer of fluid between the wall and

the hot gas stream. This method holds particular promise for air-cooled gas-turbine rotor blades where conventional convection-cooling methods become inadequate at high gas temperatures. The transpiration-cooling method also offers attractive possibilities for the cooling of other structural elements in the aircraft propulsion system, such as combustion chambers, transition ducts, turbine stators and casings, and jet-nozzle components. This method may also be used to protect the skin of missiles from aerodynamic heating effects. Additional applications for porous walls may be found in deicing where warm air is forced through the walls, and in boundary-layer control devices where suction is applied to improve flow characteristics.

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A porous material for transpiration cooling and the other applications mentioned must fulfill certain basic requirements. These requirements are:

(a) Controllable permeability which is locally uniform or changes locally in a prescribed manner to meet a required coolant-flow distribution

(b) Sufficiently wide range of permeabilities to accommodate large variations in coolant flow requirements

(c) Adequate strength for a proposed application

(d) Availability in quantity in pieces of sufficient size and thickness to meet a specific application

(e) Adaptability to conventional fabrication methods

Usually a porous material produced by sintering of powdered metals is considered for transpiration-cooling applications. However, sintered metals do not as yet satisfactorily fulfill all the previously-mentioned requirements. The applicability of other materials for the transpiration-cooling process was therefore studied. In many transpiration-cooling applications, the primary stresses are in one direction in the plane of the porous wall, as, for example, in gas-turbine rotor blades where the primary stresses are caused by centrifugal forces and act in the direction of those forces. In such a case, it is advantageous to have a porous material that is composed of fibers or wires which run parallel to the direction of these primary stresses. In the process of investigating materials which meet this idea, a type of wire cloth having the greater portion of the wires woven in one direction was selected for consideration. As woven, the wire cloth has a permeability which is too large for most transpiration-cooling applications; however, its permeability can be reduced to any desired degree by cold-rolling. The stiffness was increased by a brazing process which bonded the wires together.

The results are presented herein of an investigation conducted at the NACA Lewis laboratory of the permeability and strength of wire cloth both in its normal state and as modified by the previously-mentioned brazing and rolling processes for transpiration cooling.

Samples of wire cloth for these investigations were obtained from The W. S. Tyler Company of Cleveland. The assistance of this company and particularly Mr. Hugh Brown in the development of wire cloth as a material for transpiration cooling is gratefully acknowledged.

PREPARATION OF WIRE CLOTH

A wire cloth suitable for the outlined purpose should be such that the greater portion of the wires run in the direction of the primary stresses. A special weave called corduroy cloth fulfills this requirement. The mesh of wire cloth is designated by the number of openings per inch between wires in the warp and shoot, respectively. (See fig. 1.) In this report the wires in the shoot of the cloth are referred to as lengthwise wires, and the wires in the warp as crosswise wires. Data for the three different meshes of the wire cloth, which were investigated in this report, are contained in table I. The number of wires in the second and fourth columns was determined by actual count on the samples used. For the 20X350 wire cloth, this number deviated considerably from the nominal number.

The material in the cloth tested in this investigation is AISI type 304 stainless steel. However, the wire cloth can be manufactured from other materials as well. The wires from which the cloth is woven are in an annealed state. The weaving process itself causes some work hardening. Front and side views of such a wire cloth are shown in figure 2. This figure depicts the special type of weave which is used in the manufacturing process.

As woven the wire cloth has a permeability that is too high for most of the applications considered. However, the permeabilities may be decreased to any desired degree by a cold-rolling process. The strength of the wires is increased by this rolling process as long as the reduction in thickness stays below a certain limit, approximately half the original thickness. Front and side views of the wire cloth after it was rolled to half its original thickness are presented in figure 3. This photograph may be somewhat misleading as it gives the impression that the spaces between the wires are closed up except for the rows of dark holes. In reality, the slots that run obliquely to the surface of the cloth are still present between the wires. In addition to decreasing the permeability, the rolling process has another beneficial effect. For many applications, the surface of the transpiration-cooled wall has to be smooth. It can be seen from a comparison of figures 2 and 3 that the surface roughness is decreased considerably by the rolling process.

In order to be effective, the rolling has to be applied in the lengthwise direction, which is the axial direction of the larger number of wires. In some cases, porous material prepared in this way is undesirable because it is considerably less rigid against bending forces than a piece of solid sheet metal. The rigidity can be increased by interconnecting the wires at all places where they touch each other. Such interconnection was obtained in the following way: The wire cloth was sprayed with a low-temperature silver brazing alloy by the use of a metal spray gun; the brazing material applied this way did not close up the pores but covered the wires only on the surface facing the spray gun. A view of the surface of the sprayed cloth is shown in figure 4(a). A silver brazing alloy with a melting point of 1260° F was used in this investigation. The sprayed cloth was dipped into a salt bath at about 1400° F temperature until the sprayed alloy was brazed to the surface of the wires (figs. 4(b) and 4(c)). It can be seen that the brazing material gave a very good interconnection of the wires without closing up the spaces needed for the flow of the coolant.

The material containing no brazing material is referred to herein as "unbrazed wire cloth", and the sprayed and heated material as "brazed wire cloth". The specific application determines whether preference should be given to the brazed or the unbrazed wire cloth. An advantage of the brazed cloth is its greater stiffness, but, it is to be expected that unbrazed cloth has good vibration damping characteristics, which are desirable in many cases. Also, the permissible temperature will be higher for the unbrazed cloth. For these reasons, the investigations were conducted on both types of cloth. Air-flow tests showed that the permeability was not decreased seriously by the brazing process. The permeability of the brazed material was reduced to the desired degree by rolling after the brazing process was finished. Photographs of this material after its thickness has been reduced 15 and 37 percent of the original value are presented in figures 5(a) and 5(b), respectively. The material prepared in this way has a smooth surface and a stiffness comparable to solid sheet metal of the same thickness.

Methods were developed by The W. S. Tyler Company for joining pieces of wire cloth by a brazing process and also for interconnecting several layers of wire cloth by local application of heat in a manner corresponding to spot welding or seam welding. Of the different procedures tested at the Lewis laboratory for connecting wire cloth to a solid metal structure, spot welding was found to be most satisfactory.

PERMEABILITY OF WIRE CLOTH

The amount of coolant that can be forced through a porous material with a given pressure drop must be known for the designer to select the material and operating pressure for a specific application of transpiration cooling.

In order to determine the amount of air that will flow through rolled wire cloth of various permeabilities in both the brazed and the unbrazed state, tests were performed during which the weight rate of flow and the pressure drop across the cloth were measured.

Apparatus and Procedure

A schematic diagram of the test equipment used for determining the permeability of wire cloth is shown in figure 6. Air at room temperature and at a gage pressure of 120 pounds per square inch is filtered and passed through a pressure regulator. The air flow is controlled by a hand valve and measured by a rotameter. It then passes through a specimen of wire cloth held between two copper gaskets in a pipe-to-tube connector coupling. This arrangement is shown in detail in figure 6. The temperature and the pressure of the air passing through the rotameter are also measured.

Pieces of unbrazed wire cloth selected from sheets supplied by the manufacturer were rolled various amounts to a maximum reduction of 50 percent of their original thickness. Disks, $1\frac{3}{4}$ inches in diameter, were cut from the selected pieces and their average thicknesses were determined. These disks were then clamped tightly between the copper gaskets in the connector coupling. Air was permitted to flow through the test apparatus. The pressures on both sides of the wire-cloth specimen as well as the weight flow through it were determined. For the most part, measurements were made on three layers of the cloth stacked one on top of the other. However, in order to determine whether or not there is a difference in permeability when different numbers of layers are used, tests were also performed on one and five layers of the cloth. Similar permeability tests were made on brazed- and rolled-wire cloth.

Results of Permeability Tests

The weight rate of flow of gases through a plane wall of porous material at large pressure differences and under isothermal conditions depends on the pressure-square difference (reference 2). Therefore, the results of the permeability tests are plotted in figures 7 and 8 as the difference in the squares of the pressures on both sides of the cloth per unit of thickness of cloth against the weight rate of flow of gases through the cloth. Two mesh sizes of the unbrazed cloth (fig. 7), and three mesh sizes of brazed cloth (fig. 8) were investigated .

Each of the figures contains results with different numbers of layers at the same percentage of thickness reduction by rolling. An examination of the corresponding points reveals that the pressure-square difference per unit thickness of the cloth does not depend systematically

on the number of layers. Differences that occur in some cases are attributed to inaccuracies in the preparation of the porous cloth or the thickness measurements. Especially at large values of thickness reduction, the thickness measurement has to be extremely accurate in order to obtain reproducible results. This point is discussed in the following section. The fact that the pressure-square difference per unit thickness does not depend on the number of layers indicates that the pressure drop through a specified number of layers is the same regardless of whether the layers are placed some distance apart or stacked closely together. The two unconnected points in figure 8(b) are for data obtained in an attempt to investigate a 20X350 specimen of very low permeability. There was insufficient pressure drop available to test at higher weight-flow rates.

A comparison of unbrazed and brazed cloth of a specific mesh (figs. 7(a) and 8(a) or figs. 7(b) and 8(c), respectively) indicates that the pressure-square difference of the brazed cloth is about 20-percent larger than the pressure-square difference of unbrazed cloth with the same thickness. The brazed cloth must be rolled in order to obtain considerable reduction in the permeability. However, the difference in the pressure-square difference values of unbrazed and brazed cloth become greater at large values of thickness reduction (figs. 7 and 8). At high values, it is therefore unnecessary to roll brazed cloth as much as unbrazed cloth in order to obtain the same permeability. This fact becomes important when embrittlement is a consideration in cloths rolled to very low permeability; it is discussed in the section entitled "TENSILE STRENGTH OF WIRE CLOTH."

No consistent differences can be found between the values of the pressure-square difference per unit thickness for cloth of different meshes in either the brazed or the unbrazed condition.

Comparison With Compacted Sintered Porous Metals

A comparison of the relation between porosity and permeability of rolled wire cloth with that of some compacted sintered porous metals is of interest because such a comparison should give some indication of the nature of the flow as influenced by the geometry of the channels in both materials.

For this purpose, the porosity of the wire cloth will be calculated. The porosity is the ratio of the volume of voids V_v to the total volume V_t (all symbols are defined in the appendix):

$$f = \frac{V_v}{V_t} \tag{1}$$

or if the volume of metal V_m is used

$$f = 1 - \frac{V_m}{V_t}$$

However, the volume of the metal includes the volume of the steel V_s and the volume of the brazing alloy V_b, therefore

$$V_m = V_s + V_b$$

When the corresponding weight W and specific weight γ are used, this equation may be written

$$V_m = \frac{W_s}{\gamma_s} + \frac{W_b}{\gamma_b}$$

Then

$$f = 1 - \frac{1}{V_t}\left(\frac{W_s}{\gamma_s} + \frac{W_b}{\gamma_b}\right)$$

and because $V_t = A\tau$ where A is the surface area and τ is the thickness of the cloth

$$f = 1 - \frac{1}{\tau}\left[\frac{1}{\gamma_s}\frac{W_s}{A} + \frac{1}{\gamma_b}\frac{W_b}{A}\right] \qquad (2)$$

By this formula the porosity can be calculated because the specific weight of the steel and of the brazing material is known. The weight per unit area of the unbrazed material is W_s/A and the difference in weight of the brazed and the unbrazed material is W_b/A.

In figure 9, the porosity of rolled-wire cloth, as determined by equation (2), is plotted against the percentage reduction in original thickness. The value of the porosity of unbrazed wire cloth at a given value of thickness reduction increases with an increase in the ratio of the diameter of the crosswise wires to the diameter of the lengthwise wires (see table I). A large diameter ratio causes more bending of the wires in weaving and consequently more void space. The amount of braze material added to the cloth was largest for the 28X500 mesh size. This fact explains why the reduction in porosity by the brazing process was largest for this type of cloth.

The permeability coefficient K is defined by Darcy's law (reference 3) as follows:

$$\frac{p_1^2 - p_2^2}{\Sigma\tau} = \frac{1}{K}(2RT\mu)G \tag{3}$$

where $\Sigma\tau$ is the total thickness of a number of layers of cloth in series. A linear relation between the pressure-square difference and the weight rate of flow is assumed in this law. Actually, the relation is not quite linear (figs. 7 and 8). This relation was expressed in reference 2 by the equation

$$\frac{p_1^2 - p_2^2}{\Sigma\tau} = \alpha(2RT\mu)G + \beta\frac{2RT}{g}G^2 \tag{4}$$

By equating equations (3) and (4) and solving for K, it is found that

$$K = \frac{1}{\alpha}\frac{1}{1 + \frac{\beta}{\alpha\mu g}G} \tag{5}$$

This equation shows that the permeability coefficient actually varies somewhat with the weight rate of flow and the temperature (viscosity) of the fluid passing through the porous material as well as the configuration of the passages in the material. A permeability coefficient based on Darcy's law is used herein in order to compare the wire cloth with compacted sintered metals which were evaluated on this same basis in reference 4. For small values of weight flow, this method gives a good approximation of the permeability coefficient K in equation (5) because the second term $\frac{\beta}{\alpha\mu g}G$ in the denominator becomes small as compared with the first term. For large values of weight flow, the effects of this second term become appreciable and cannot be neglected.

The permeability coefficient K or $1/\alpha$ is plotted against the percentage reduction in original thickness in figure 10. The test points appear to be grouped around two curves, one for brazed cloth and one for unbrazed cloth.

Finally, the porosity was plotted against the permeability coefficient in figure 11 along with test results on sintered metal compacts obtained from reference 4. From figure 11 it is seen that although the same range of porosities is considered the range of permeability coefficients for the wire cloth is much greater than that of the sintered

compacts. For a small change in porosity of the wire cloth, it is possible to obtain a large change in the permeability. On the other hand, because the porosity is mainly controlled by the rolling process, a small error in obtaining a required thickness of the cloth means a relatively large error in the permeability. As an example, it is found from figures 9 and 11 that for brazed 20X250 mesh cloth having a porosity in the region of 14 percent an error of ±0.0001 inch causes a ±13 percent variation in the permeability coefficient. The rolling process must therefore be controlled with extreme care to obtain reproducible results. This fact also explains the scatter in figures 9 and 10. For equal permeability values, the required porosity of sintered material is generally greater than that of the wire cloth probably because of the smaller cross section and the more tortuous course of the passages.

TENSILE STRENGTH OF WIRE CLOTH

Experimental Procedure and Results

Sufficient strength is an important consideration in many applications of porous materials to transpiration cooling as was mentioned in the INTRODUCTION. The three meshes of wire cloth tested were woven from AISI type 304 stainless steel, which has a tensile strength in the annealed state of 87,000 pounds per square inch. This material will elongate about 65 percent in a 2-inch gage length before rupturing (reference 5). The manufacturer of the cloth estimates that a 20-percent elongation occurs during the weaving process, and that this cold-working of the material raises the tensile strength of the cloth to about 100,000 pounds per square inch. The effect of cold work on the tensile strength and percent elongation of AISI type 302 stainless steel (reference 5) is shown in figure 12. The behavior of AISI type 304 stainless steel is similar except for a slightly higher rate of work hardening because of the lower carbon content. It can readily be seen from these curves that in addition to bringing the permeability of the wire cloth into a desirable range, the rolling will increase the tensile strength and reduce the percentage elongation.

Tensile tests have been made at room temperature on rolled and unrolled wire cloth, both brazed and unbrazed. These tests were made on strips of mesh approximately 0.8 inch wide and 10 inches long. In order to obtain better gripping in the jaws of the testing machine, the ends of the test strips were coated with soft solder. Particularly with the unbrazed cloth this coating insured that all wires would be stressed equally. During the tests, the load was increased progressively in increments of 100 pounds and the elongation of the test specimen was measured at each loading up to and including the breaking load. The elongation of rolled specimens of brazed and unbrazed cloth is shown in figures 13 and 14 as percentage elongation in 4 inches. The percentage

elongation due to tensile stress decreases with increased amount of rolling performed on the cloth. This decrease is partly due to compacting of the woven structure, and partly to the increase in the hardness of the material. The marked effect of cold-working on the elongation of AISI type 302 stainless steel is apparent in figure 12. Cold-working of AISI type 304 stainless steel will produce similar effects. If the allowable stresses in a structure are determined by the elongation, then the stresses must be kept below 0.5 to 0.7 of the tensile strength depending on the amount of rolling (figs. 13 and 14).

The effects of rolling on the tensile strength of the wire cloth are shown in figures 15 and 16. In this report, the term tensile strength refers to the ultimate tensile strength unless otherwise indicated. The left sides of both figures were computed by dividing the breaking load by the sum of the cross-sectional areas of the lengthwise wires as determined from the diameters before rolling and the actual number of wires per inch given in table I. For structural elements like turbine blades which have to carry their own weight in a centrifugal field, the ratio of the tensile strength σ to the specific weight γ is a value more suitable for comparing different materials than the tensile strength σ alone. Also, for nonrotating parts such as combustion-chamber liners, the weight is the main factor limiting the thickness of the material. In general, the ratio σ/γ is therefore the best basis for a comparison of different materials for aircraft structural components. All the porous materials which will be compared herein are manufactured from 18-8 stainless steel. A reduced tensile strength σ' was therefore determined by multiplying the strength - specific-weight ratio by the specific weight γ_s of the stainless steel:

$$\sigma' = \frac{\sigma}{\gamma} \gamma_s \tag{6}$$

This value can be compared with the familiar strength values of solid stainless steel for which $\gamma = \gamma_s$.

For the wire cloth, the reduced tensile strength was determined in the following way: The tensile strength σ is defined by the equation

$$\sigma = \frac{F}{a} \tag{7}$$

The specific weight of a specimen of the cloth of length L, cross-sectional area a, and weight W is

$$\gamma = \frac{W}{aL}$$

The reduced tensile strength for the cloth is therefore

$$\sigma' = \frac{F}{W/L} \gamma_s \tag{8}$$

This strength can be calculated from the measured values of the breaking force and weight per unit length of the specimen used for the rupture test. The right sides of figures 15 and 16 show these reduced tensile strengths. The value of the reduced tensile strength σ' is always lower than the value of the tensile strength σ because in computing the reduced strength the lengthwise wires are considered to carry in addition to their own weight the weight of the crosswise wires. The values of the reduced strength σ' increase at a faster rate with reduction of thickness by rolling than the values of the tensile strength σ. This more rapid increase is explained by the fact that the length of the wires increased and the corresponding cross-sectional area decreased in the rolling process; a fact which is accounted for in the determination of the reduced strength σ', whereas the strength σ is based on the nominal cross-sectional area before rolling. The difference between the original and the reduced strength is larger for the brazed 28X500 mesh cloth than for the two other types because the weight of the 28X500 mesh cloth was increased 30 percent by the brazing process as compared with 16 percent for the 20X250 type and 17 percent for the 20X350 type. It is probably possible to reduce the amount of weight addition from the brazing of the 28x500 mesh cloth by maintaining a closer control on the spraying process.

As shown in figure 15, the tensile strength of the unbrazed cloth reaches a maximum when the cloth has been reduced 40 percent in original thickness by rolling. Although the tensile strength of the brazed cloth increases even after a 45-percent reduction in original thickness with the exception of the 20x350 type (fig. 16), a practical limit is reached at about 40 or 45 percent because the material becomes too brittle to bend beyond this point.

Two specimens of 20X250 brazed wire cloth reduced 40 percent in original thickness were tested for tensile strength in the direction of the crosswise wires with an average result of 150,000 pounds per square inch. This tensile strength is based on the nominal cross-sectional areas of the crosswires as listed in table I. This value is higher than that for the tensile strength σ of the lengthwise wires, as the crosswise wires are less deformed by the rolling process than are the lengthwise wires. However, because the number of crosswise wires per inch is much less than the number of lengthwise wires, the strength of the cloth in the crosswise direction will be only a fraction of the strength in the lengthwise direction.

Comparison With Compacted Sintered Porous Metals

Usually sintered porous metals are considered as material for transpiration-cooled walls. The strength of compacted sintered porous metals as described in reference 4 will therefore be compared with the strength of wire cloth. Two of the porous metals (designated in figs. 11, 17, and 18 as the Unexcelled Powder and the Hardy compacts) were produced from AISI type 302 stainless-steel powder. The third type of porous metal compact (designated in figs. 17 and 18 as VA compacts) was made from atomized powder of AISI type 301 stainless steel. The comparison will be made for the reduced tensile strength σ'. From the values of tensile strength σ given in reference 4, a reduced tensile strength σ' was determined as follows: The ratio of the specific weight of the porous metal to the specific weight of stainless steel can be expressed in terms of porosity f of the porous metals.

$$\frac{\gamma}{\gamma_s} = 1 - f$$

The reduced tensile strength is therefore

$$\sigma' = \frac{\sigma}{1-f} \tag{9}$$

This evaluation credits the porous material with its lighter weight which is advantageous for aircraft applications. The reduced tensile strengths of the porous compacts and the wire cloth are compared for various values of porosity in figure 17, where the curves for the wire cloth were obtained by cross-plotting figures 9, 15, and 16. The tensile strengths of the 20X250 mesh and 20X350 mesh cloth, both brazed and unbrazed, are from 2 to 3 times that of the sintered compacts for a range of porosities between 15 and 20 percent. The reduced tensile strength of the brazed 28X500 mesh cloth is about $1\frac{1}{2}$ to 2 times that of the sintered compacts for this same range of porosities.

A further strength comparison between the wire cloth and the porous metals was made on the basis of the permeability coefficient K defined in the previous section. The results of this comparison are given in figure 18. Permeability data for the porous metals were obtained from reference 4, and the strength figures for the wire cloth are determined from cross plots of figures 10, 15, and 16. The strengths of the wire cloth are as much as 4 times higher in the range of permeabilities considered than the strengths of the compacted sintered materials (fig. 18). These comparisons are on the basis of the ultimate strengths of the materials, but even if the working strengths of the wire cloth, which are shown in figures 13 and 14 to be from 60,000 to 80,000 pounds per square inch, are compared with the ultimate strengths of the porous compacts, the wire cloth is still about twice as strong.

Strength of Connections Between Wire Cloth and Solid Metals

Various methods of attaching the wire cloth to a supporting structure have been considered. Tests were made on the use of spot-welding to determine the strength of such an attachment and the amount of surface interruption caused. Specimens of brazed 20X250 mesh cloth reduced 40 percent in original thickness were spot-welded to the edge of 0.040-inch-thick fins using a 1/32-inch-diameter electrode. The shear strength per spot weld for such an attachment was found to be upwards of 150 pounds. This strength is comparable to that obtained on a 0.018-inch-thick strip of sheet metal in the same test. No measurement of tensile strength of the spot welds was made, but from tests to determine the deflection of the cloth under differential air pressure, it may be concluded that any spacing of spot welds which will keep this deflection in a range comparable to casting tolerances for turbine blade profiles (about 0.005 in. deviation in 0.25 in. linear distance) will have sufficient strength to withstand any differential pressure likely to be used in transpiration cooling.

SUMMARY OF RESULTS

An experimental investigation was conducted to determine the permeability and strength characteristics of wire cloth for use as the porous material for transpiration-cooled walls and the following results were obtained:

1. By cold-rolling of corduroy wire cloth, a porous material may be obtained with a wide range of permeabilities, which should cover most requirements for transpiration-cooled walls.

2. In the range of low porosities, small changes in the reduction of thickness by rolling caused very large changes in the permeability. The rolling had to be very carefully controlled in order to obtain reproducible results.

3. The tensile strength at room temperatures increased with moderate amounts of rolling but started to decrease for the unbrazed material when the thickness had been reduced to approximately 60 percent of the original value.

4. The stiffness of the cloth against bending forces was increased considerably by a brazing process that interconnected the wires where they touched each other without closing up the channels necessary for the coolant flow.

5. The tensile strength of the wire cloth at room temperature based on the sum of the wire cross sections in the stress direction was increased by the brazing process.

6. The tensile strengths of the wire cloth were in the range of values between 100,000 and 130,000 pounds per square inch. The reduced tensile strength, which was introduced in order to evaluate the material properly for aircraft application, comprised values between 80,000 and 120,000 pounds per square inch with the exception of brazed 28X500 mesh cloth, which had values around 70,000 pounds per square inch.

7. As compared with sintered porous material made from stainless-steel powder, the reduced tensile strength of 20X250 and 20X350 mesh wire cloth in the direction of the larger number of wires was 2 to 3 times as large, and the reduced tensile strength of brazed 28X500 wire cloth from $1\frac{1}{2}$ to 2 times as large.

8. Interconnection between layers of wire cloth was accomplished by a seam brazing process, whereas for a connection with solid metal parts, spot-welding proved satisfactory.

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APPENDIX - SYMBOLS

The following symbols are used in this report:

A	surface area, sq in.
a	cross-sectional area, sq in.
F	force, lb
f	porosity, dimensionless
G	weight rate of flow, lb/(sec)(sq in.)
g	gravitational constant, in./$(\text{sec})^2$
K	permeability coefficient, sq in.
L	length, in.
p	static pressure, lb/sq in.
R	gas constant, in./$^\circ$R
T	static temperature, $^\circ$R
V	volume, cu in.
W	weight, lb
α	constant, in.^{-2}
β	constant, in.^{-1}
γ	specific weight, lb/cu in.
μ	absolute viscosity, (lb)(sec)/sq in.
Σ	summation, dimensionless
σ	tensile strength, lb/sq in.
σ'	reduced tensile strength, lb/sq in.
τ	thickness of one layer of porous material, in.

Subscripts:

1 side of porous material at high pressure

2 side of porous material at low pressure

b braze

m metal

s steel

t total

v voids

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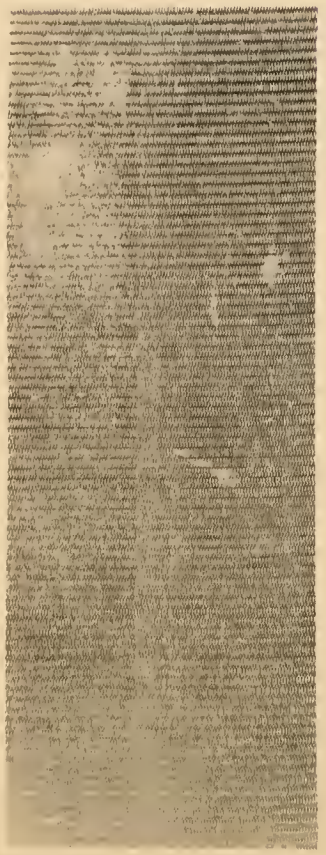
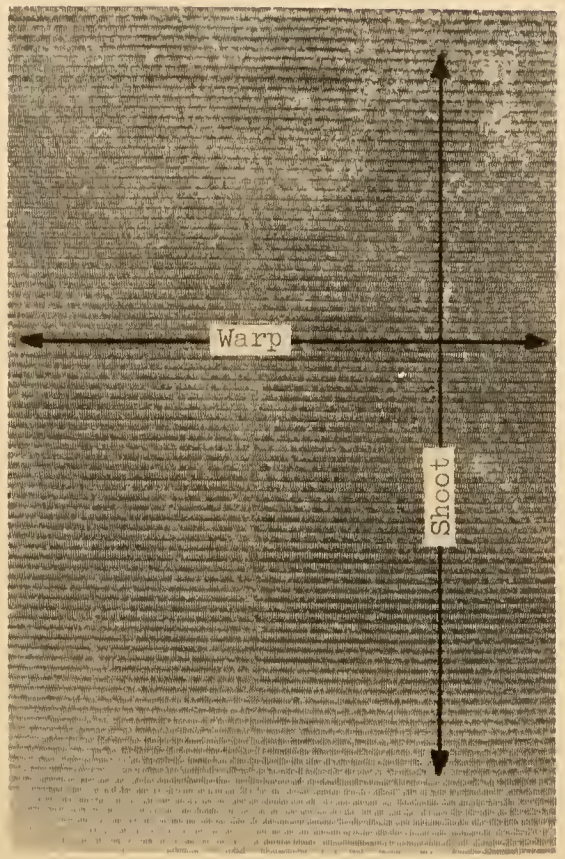
TABLE I - SPECIFICATIONS FOR THREE MESHES OF WIRE CLOTH

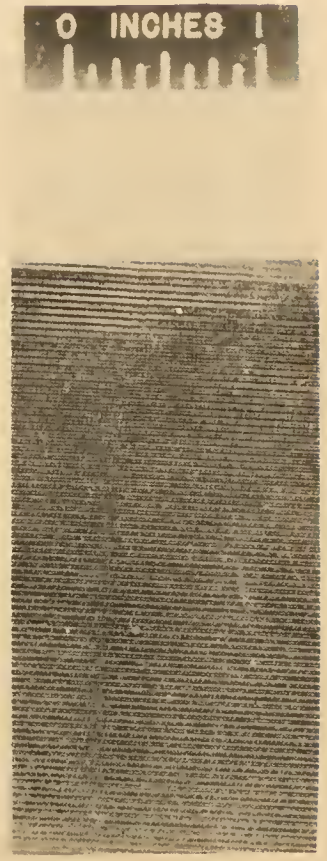
Mesh	Lengthwise wires		Crosswise wires		Original thickness of wire cloth as woven (in.)
	Number per in.	Diameter (in.)	Number per in.	Diameter (in.)	
20X250	250	0.008	20	0.010	0.0269
20X350	315	.0065	20	.010	.0238
28X500	496	.004	28	.008	.0169



(a) Mesh, 20X250.



(b) Mesh, 20X350.



(c) Mesh, 28X500.

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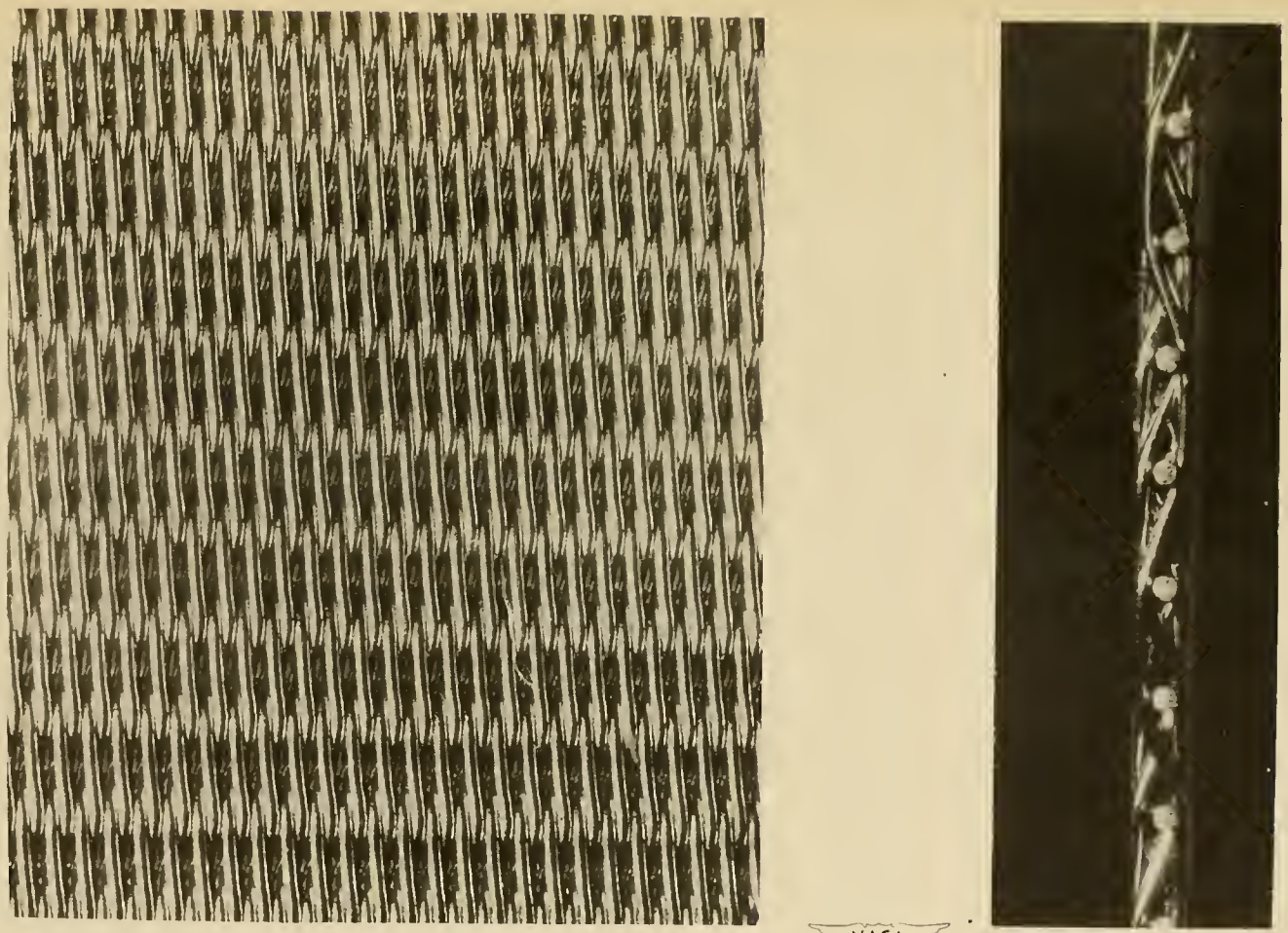
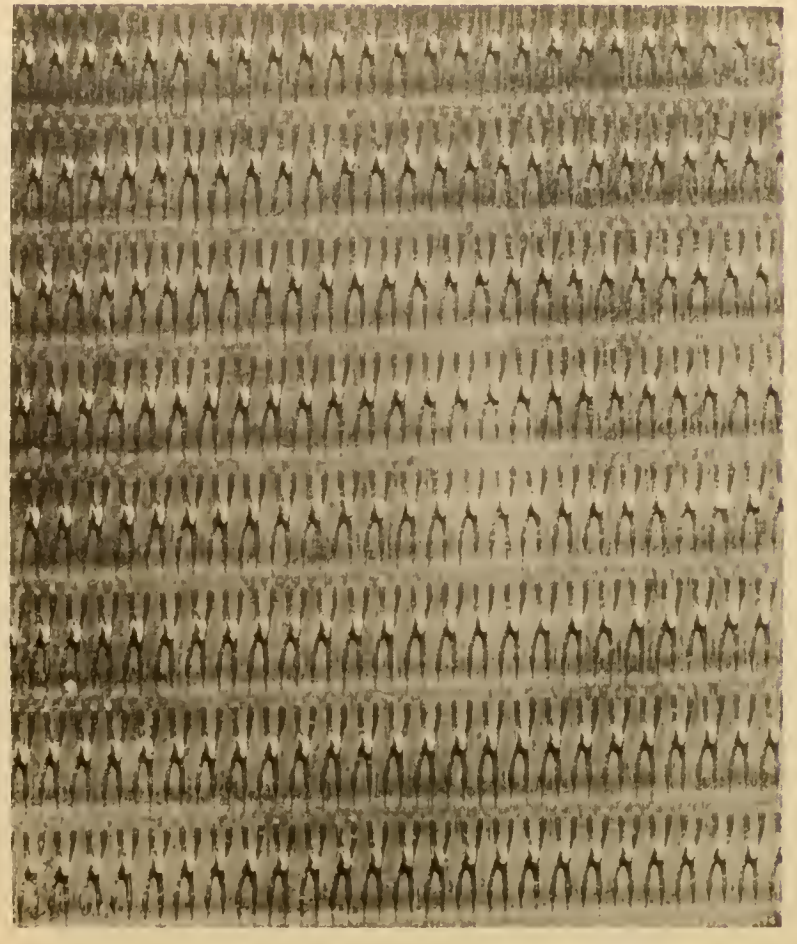
Figure 1. - Three mesh sizes of stainless-steel corduroy wire cloth as woven.



(a) Front view

(b) Side view.

Figure 2. - As woven 20x250 mesh corduroy wire cloth. (X10)



(a) Front view.

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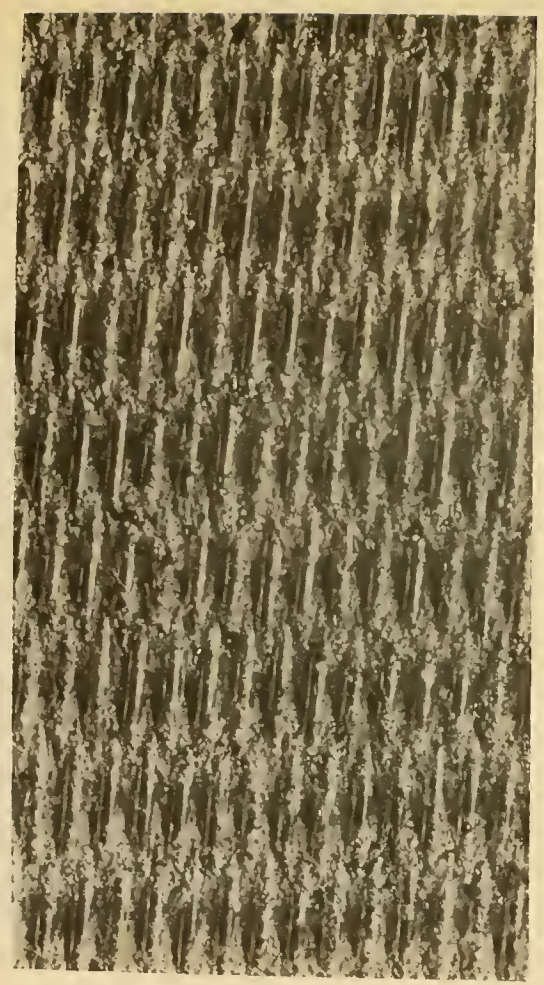
(b) Side view.

Figure 3. - 20x250 Mesh corduroy wire cloth after reduction of 50 percent in original thickness by cold-rolling. (X10)



(a) After spraying with silver brazing alloy.

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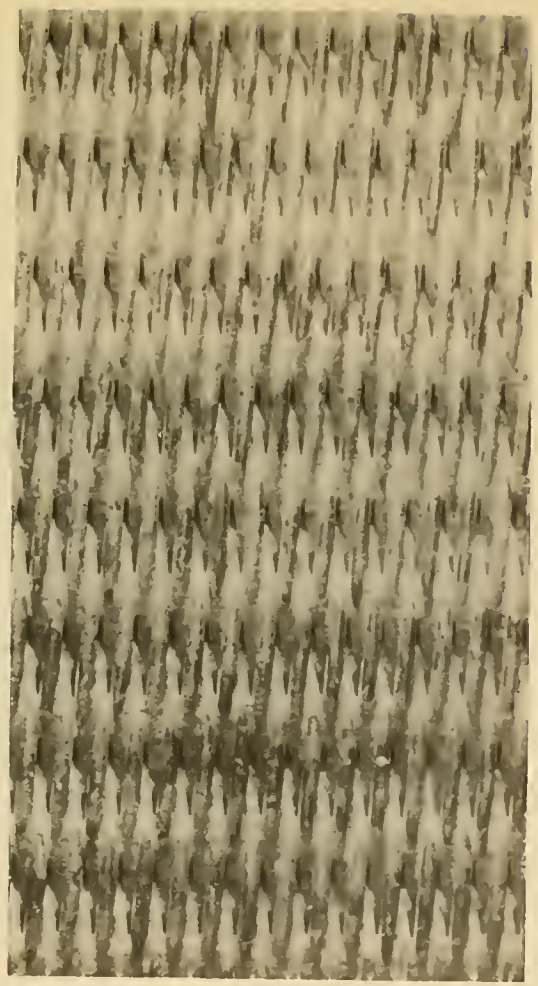

(b) After dipping in salt bath at 1400° F.

(c) Edge view of wire cloth shown in figure 4(b).

Figure 4. - Results of brazing process on 20X250 mesh corduroy wire cloth. (X10)

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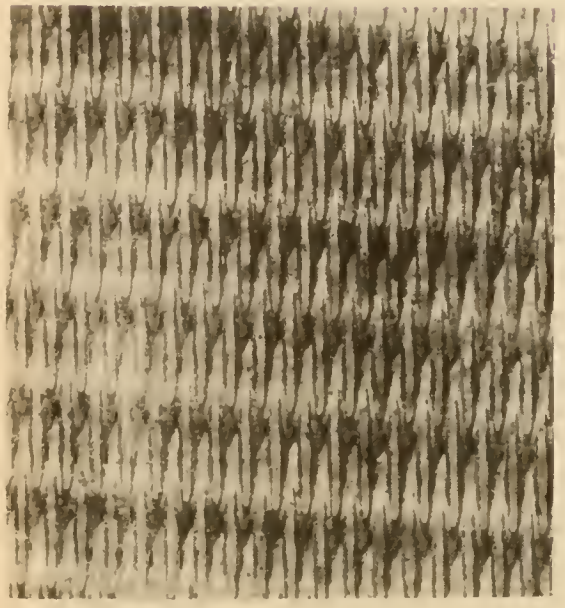
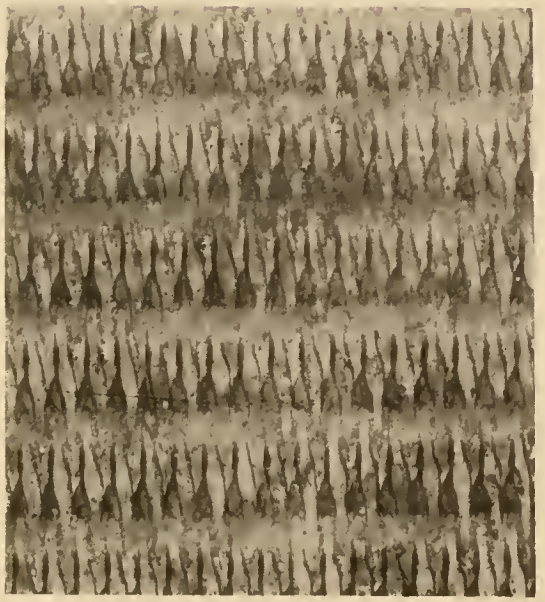
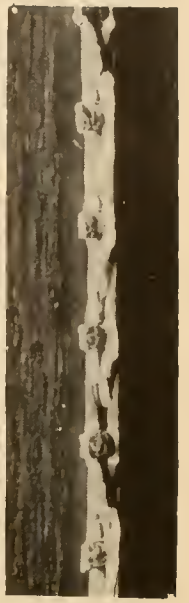


(a) 18-Percent reduction in original thickness.



(b) 37-Percent reduction in original thickness.



(c) Edge view of wire cloth shown in figure 5(b).

Figure 5. - Results of brazing process on 20X250 mesh corduroy wire cloth after cold-rolling. (X10)

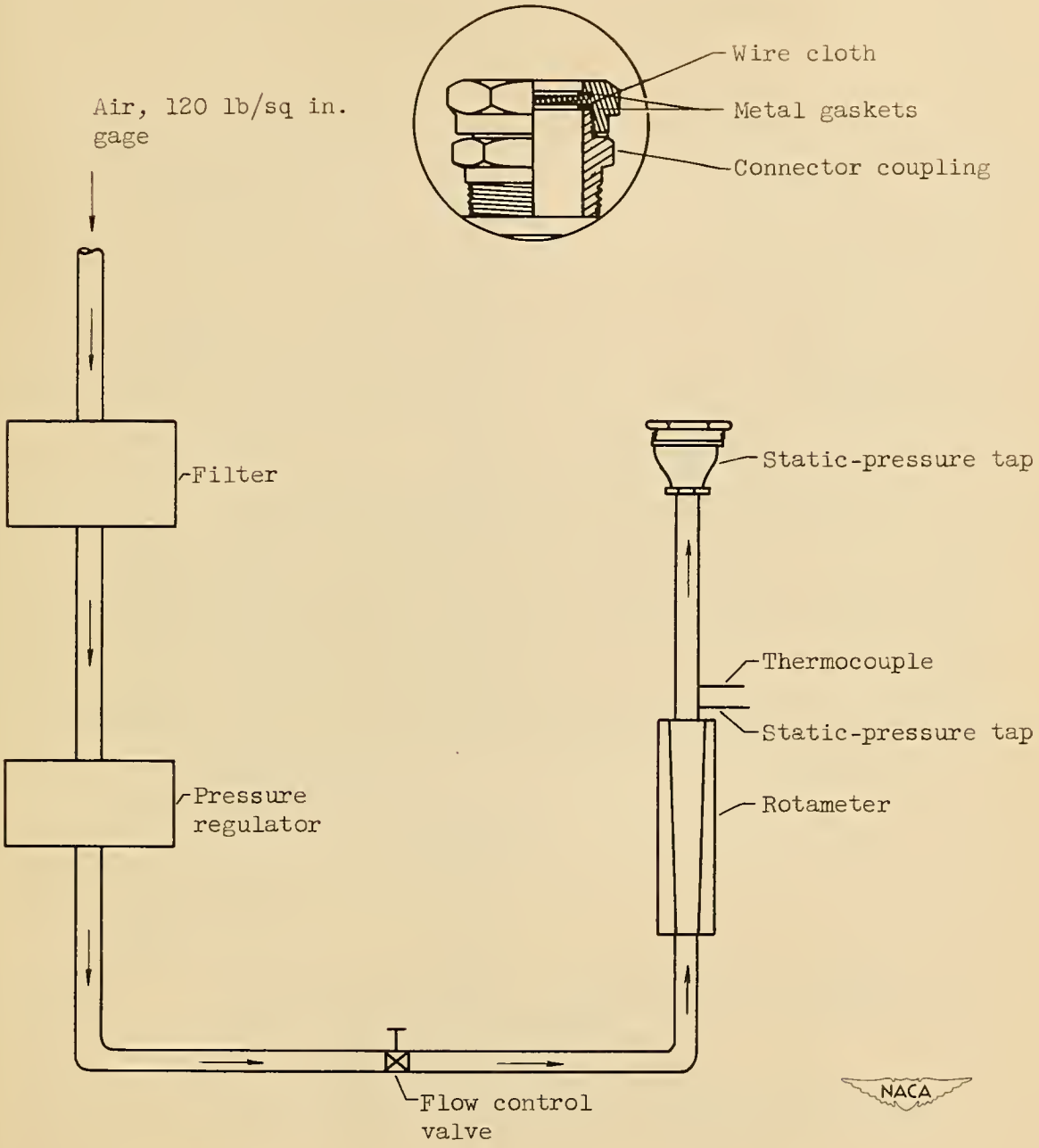
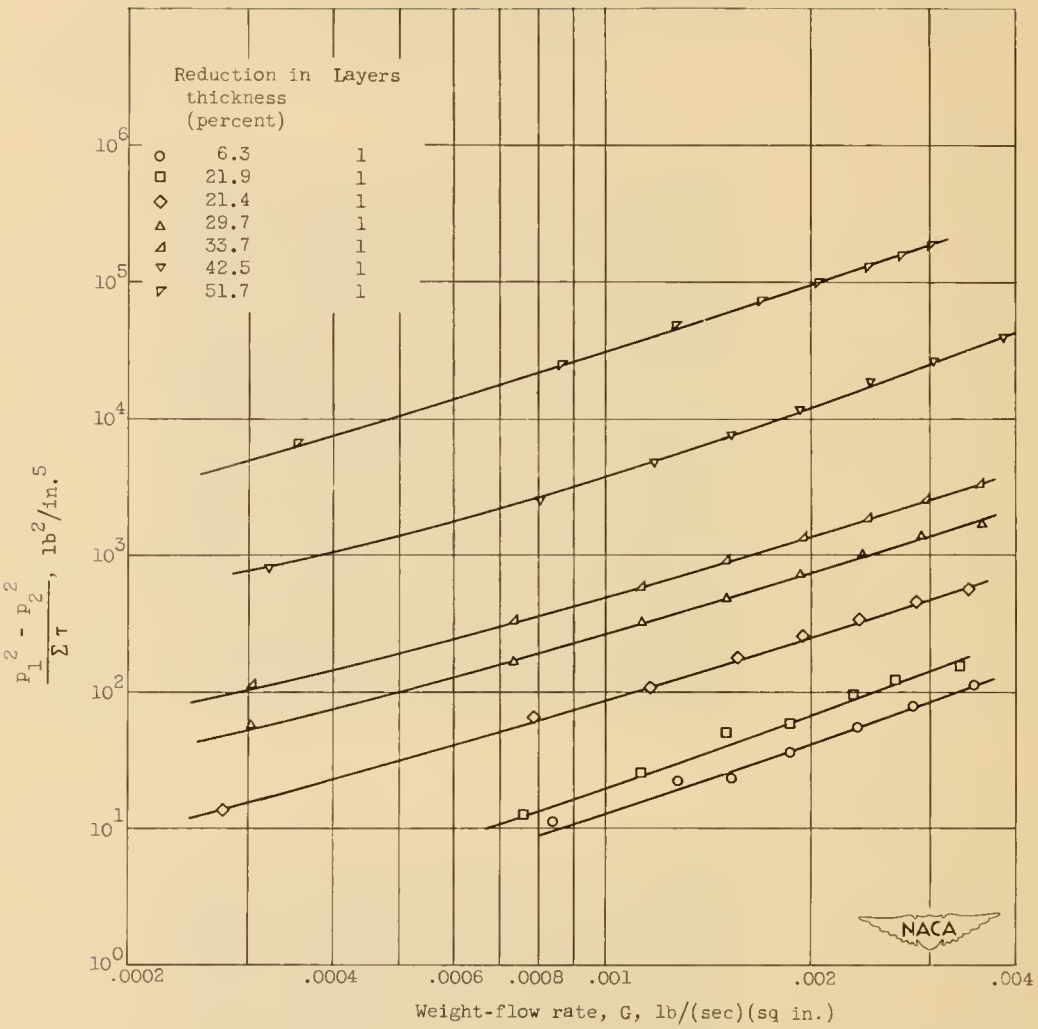
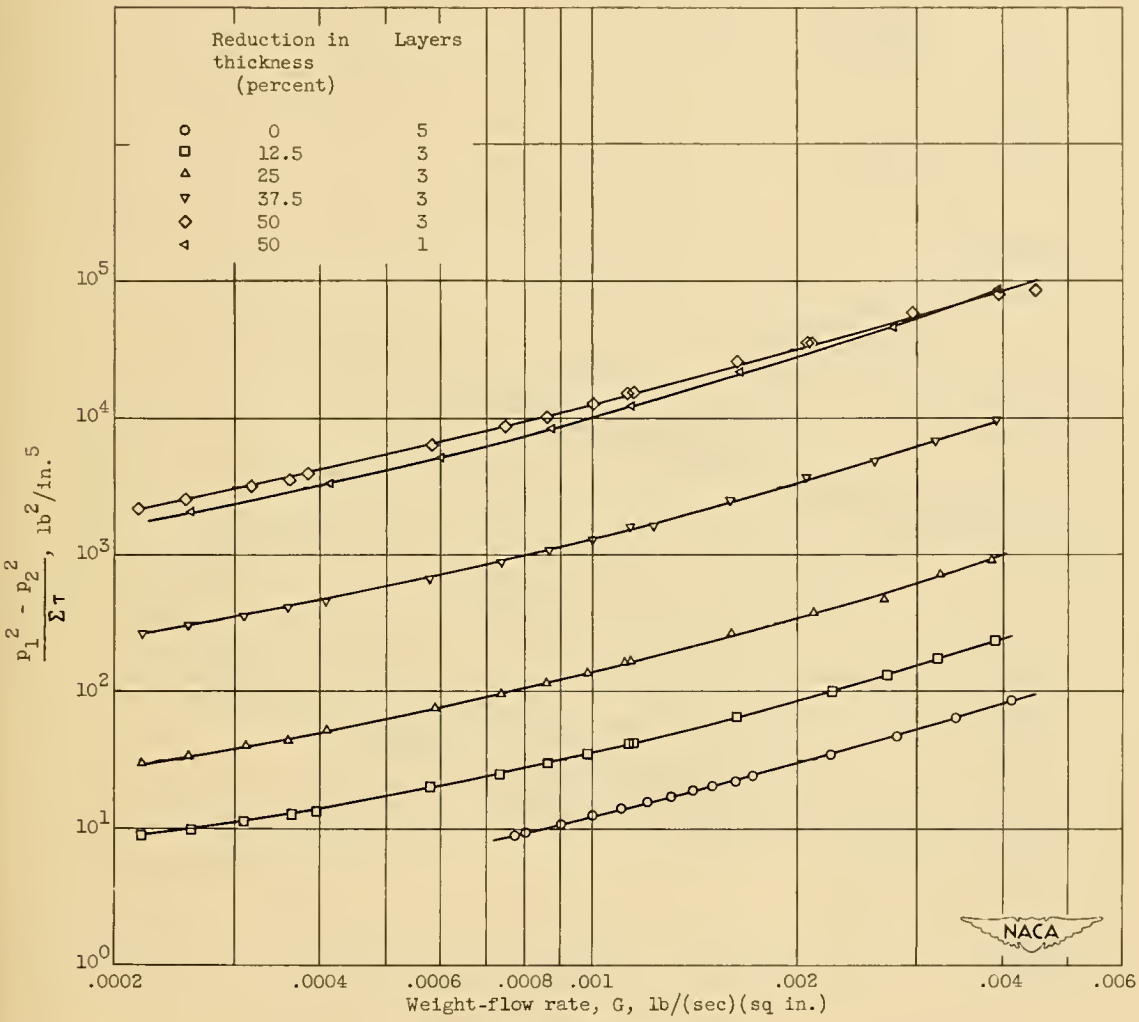


Figure 6. - Schematic diagram of test equipment for measuring air flow through specimens of wire cloth.



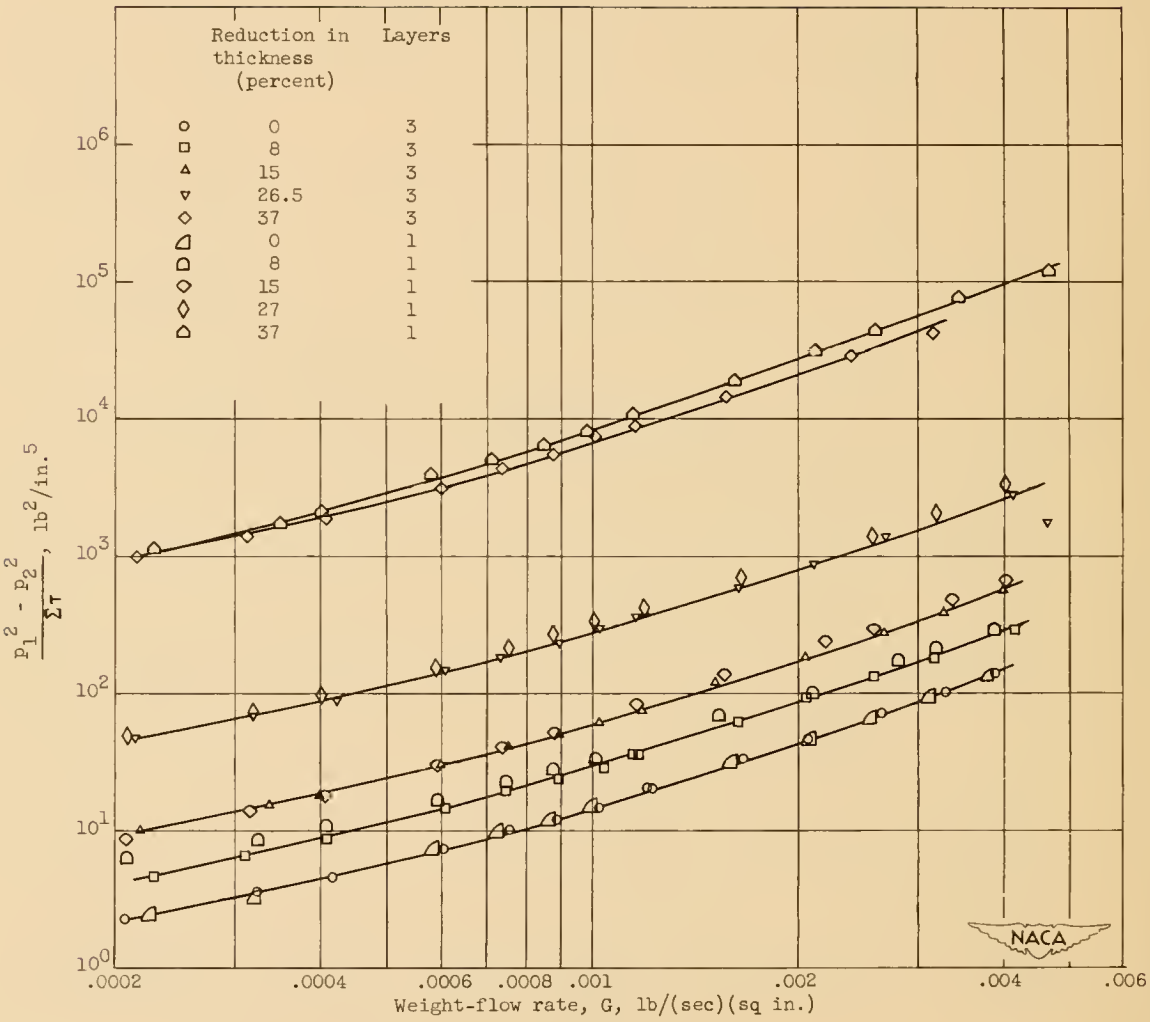
(a) Mesh, 20X250.

Figure 7. - Correlation of air-flow data for unbrazed and rolled stainless-steel corduroy wire cloth.



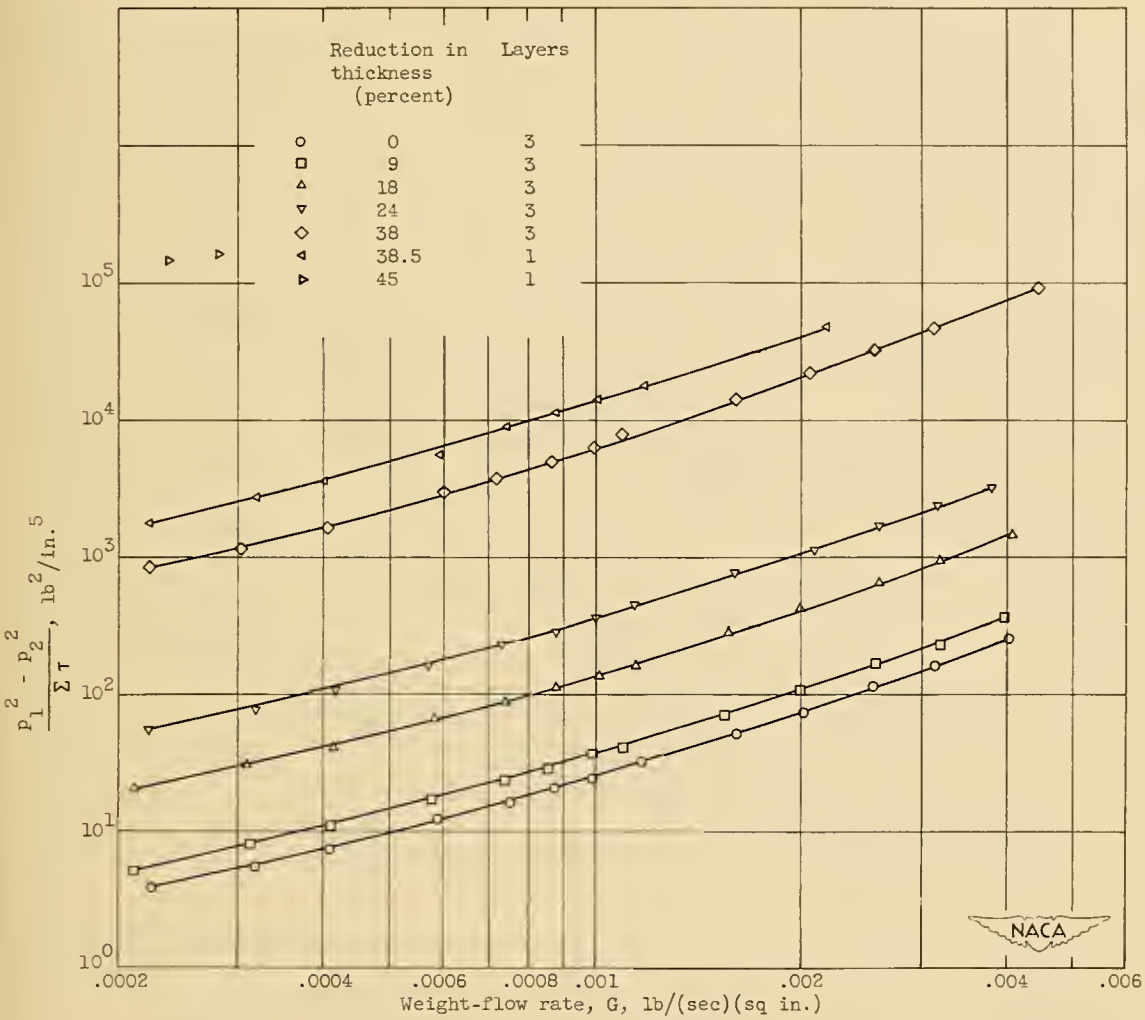
(b) Mesh, 28X500.

Figure 7. - Concluded. Correlation of air-flow data for unbrazed and rolled stainless-steel corduroy wire cloth.



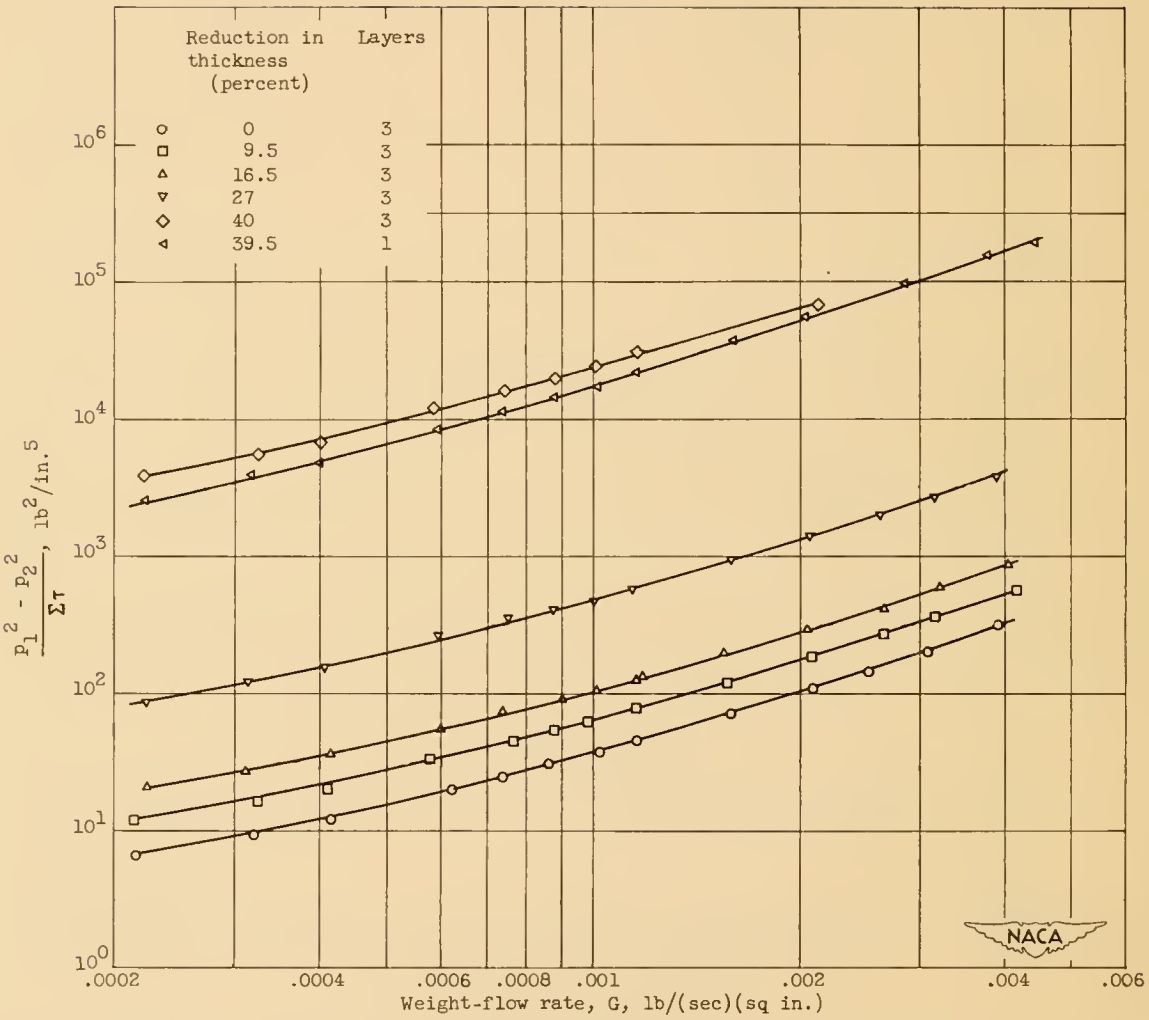
(a) Mesh, 20X250.

Figure 8. - Correlation of air-flow data for brazed and rolled stainless-steel corduroy wire cloth.



(b) Mesh, 20X350.

Figure 8. - Continued. Correlation of air-flow data for brazed and rolled stainless-steel corduroy wire cloth.



(c) Mesh, 28X500.

Figure 8. - Concluded. Correlation at air-flow data for brazed and rolled stainless-steel corduroy wire cloth.

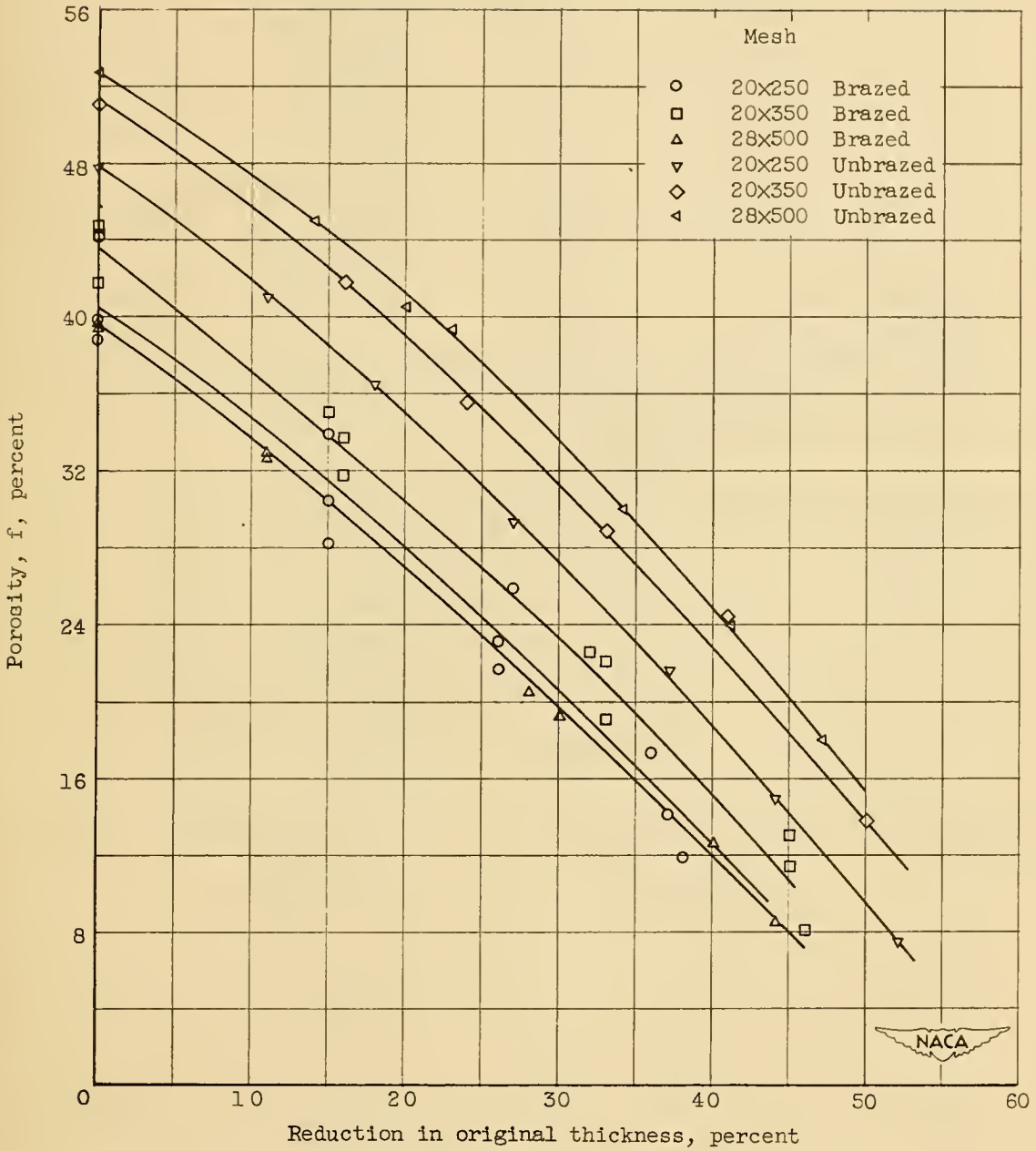


Figure 9. - Effect of rolling on porosity of brazed and unbrazed wire cloth in three mesh sizes.

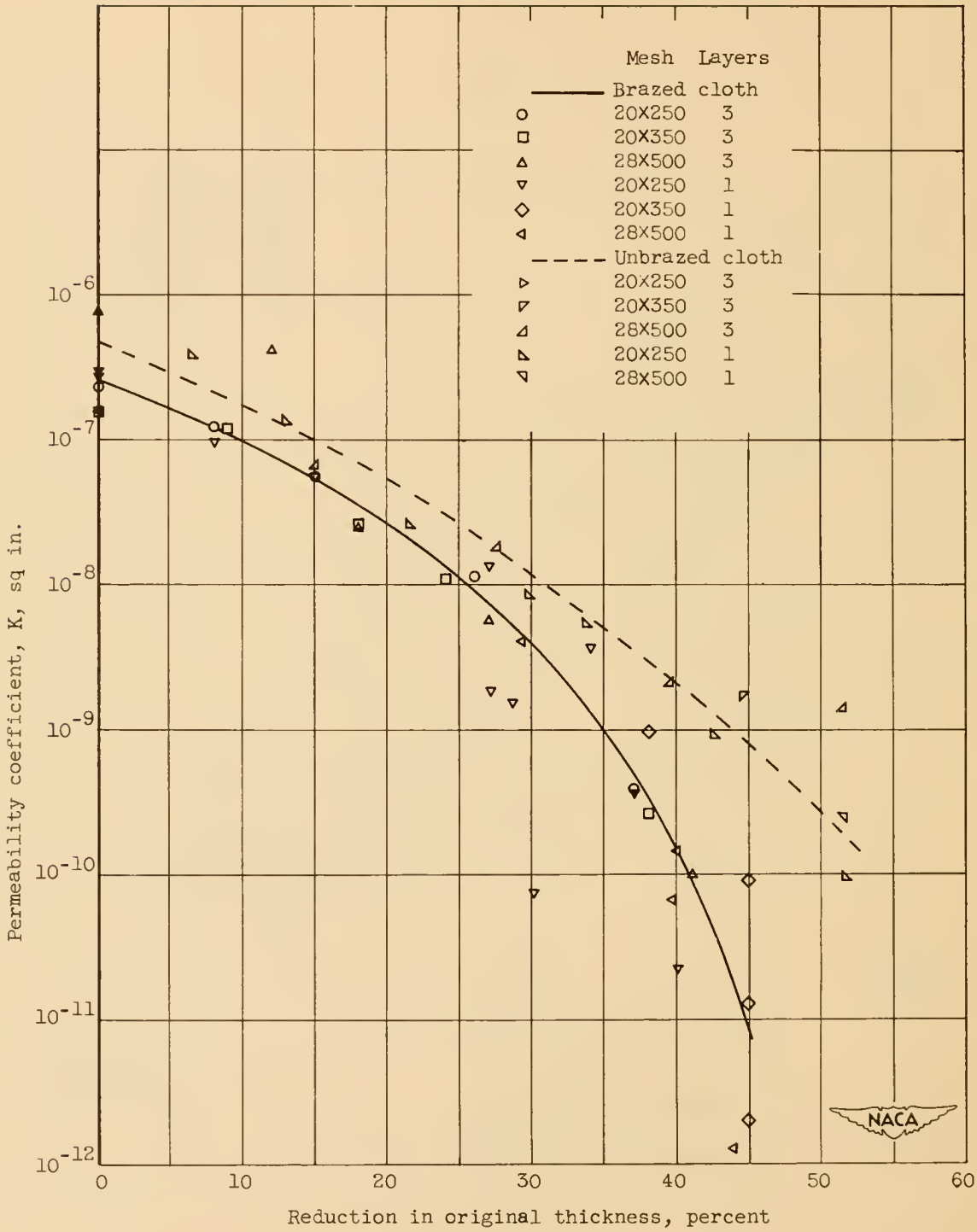


Figure 10. - Effect of rolling on permeability coefficient of brazed and unbrazed wire cloth in three mesh sizes.

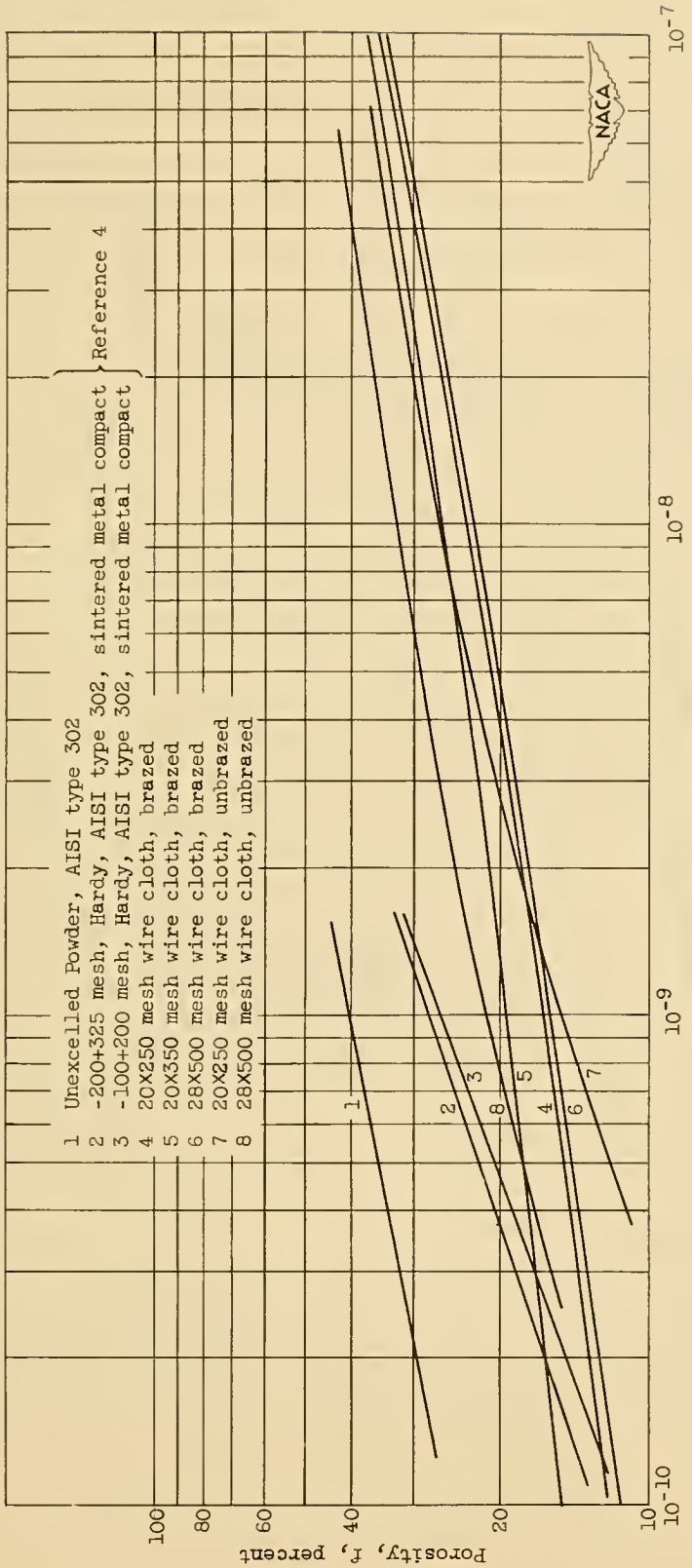


Figure 11. - Comparison of porosity and permeability coefficient for brazed and unbrazed rolled stainless-steel corduroy wire cloth and some sintered-metal compacts.

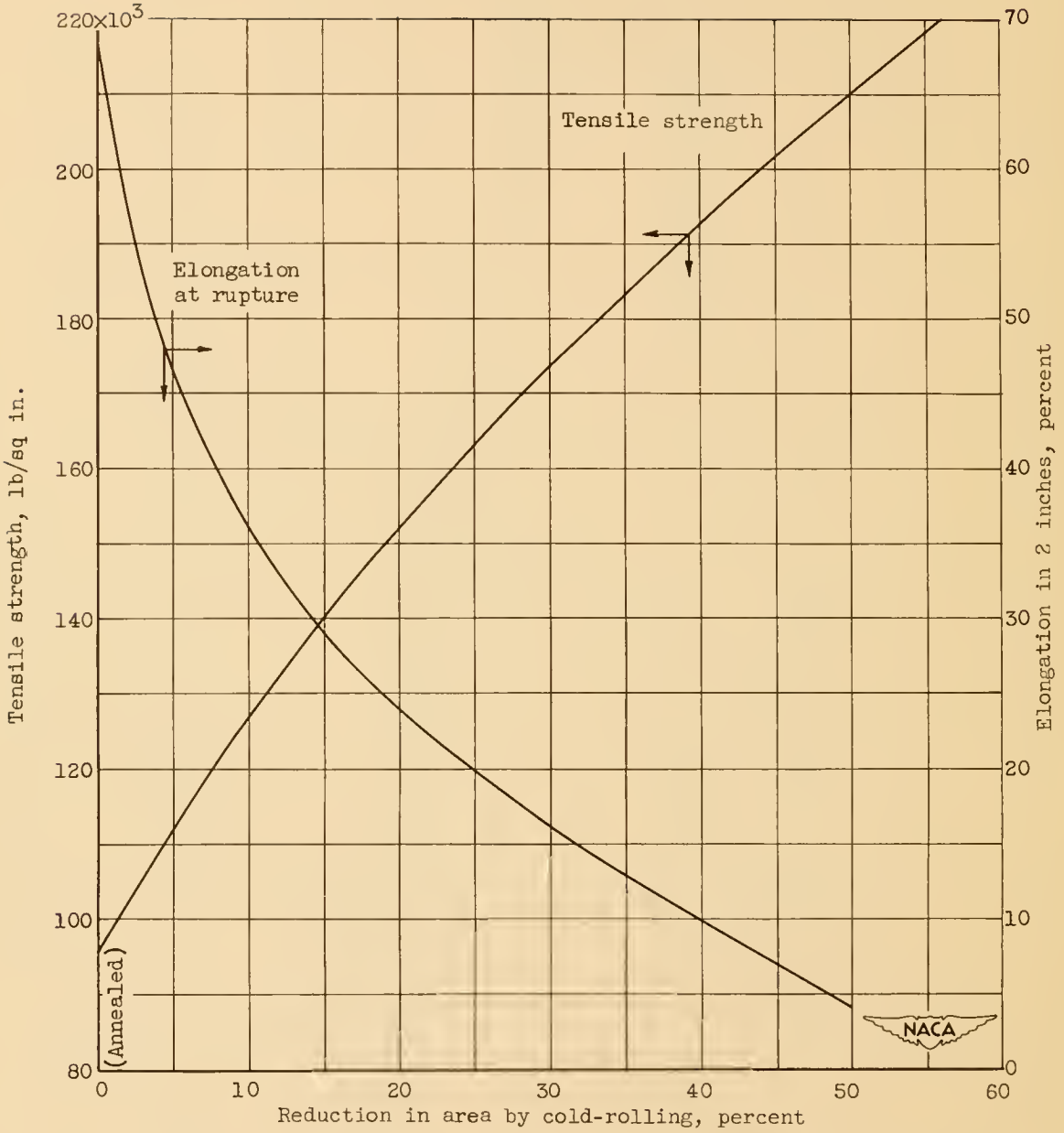
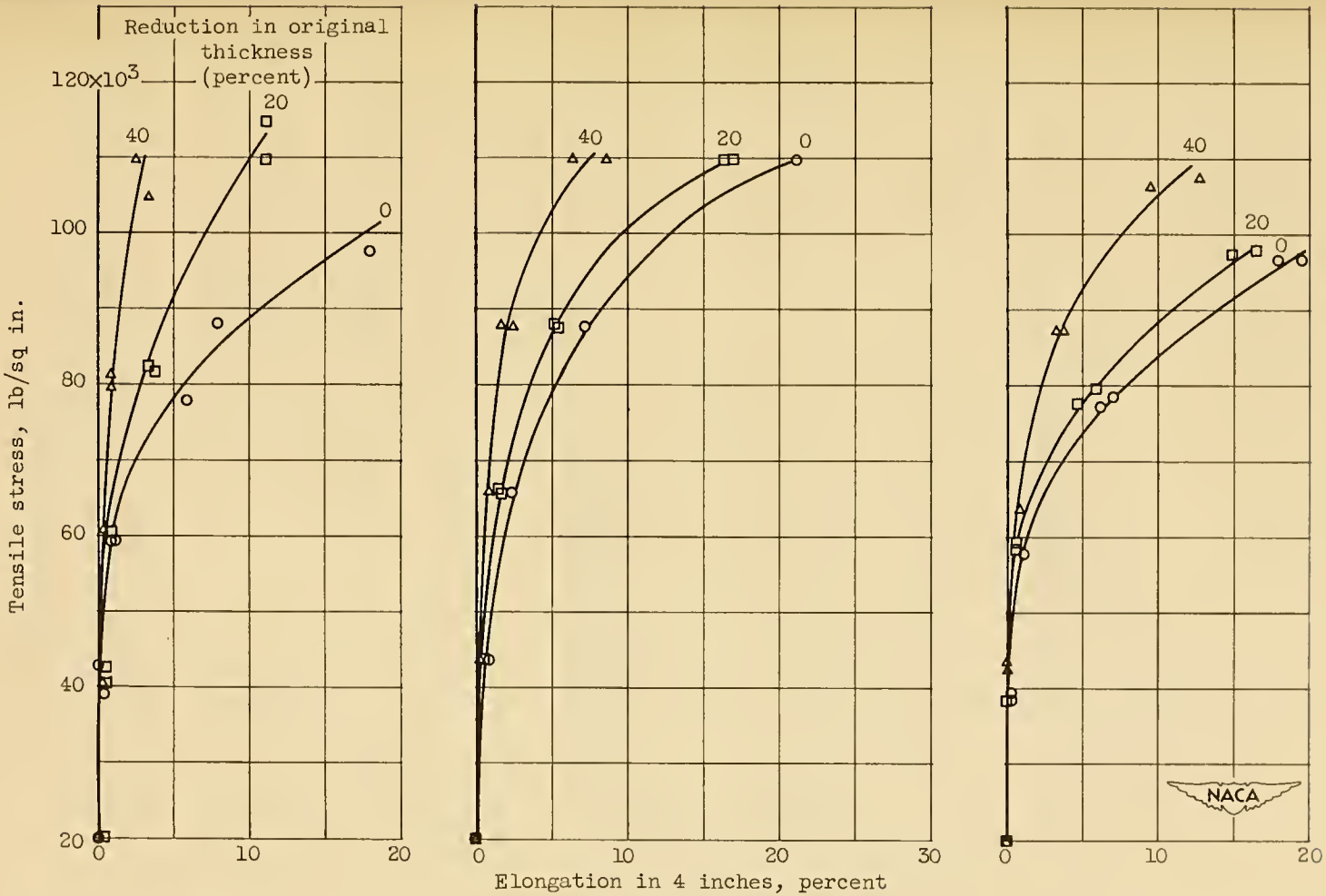
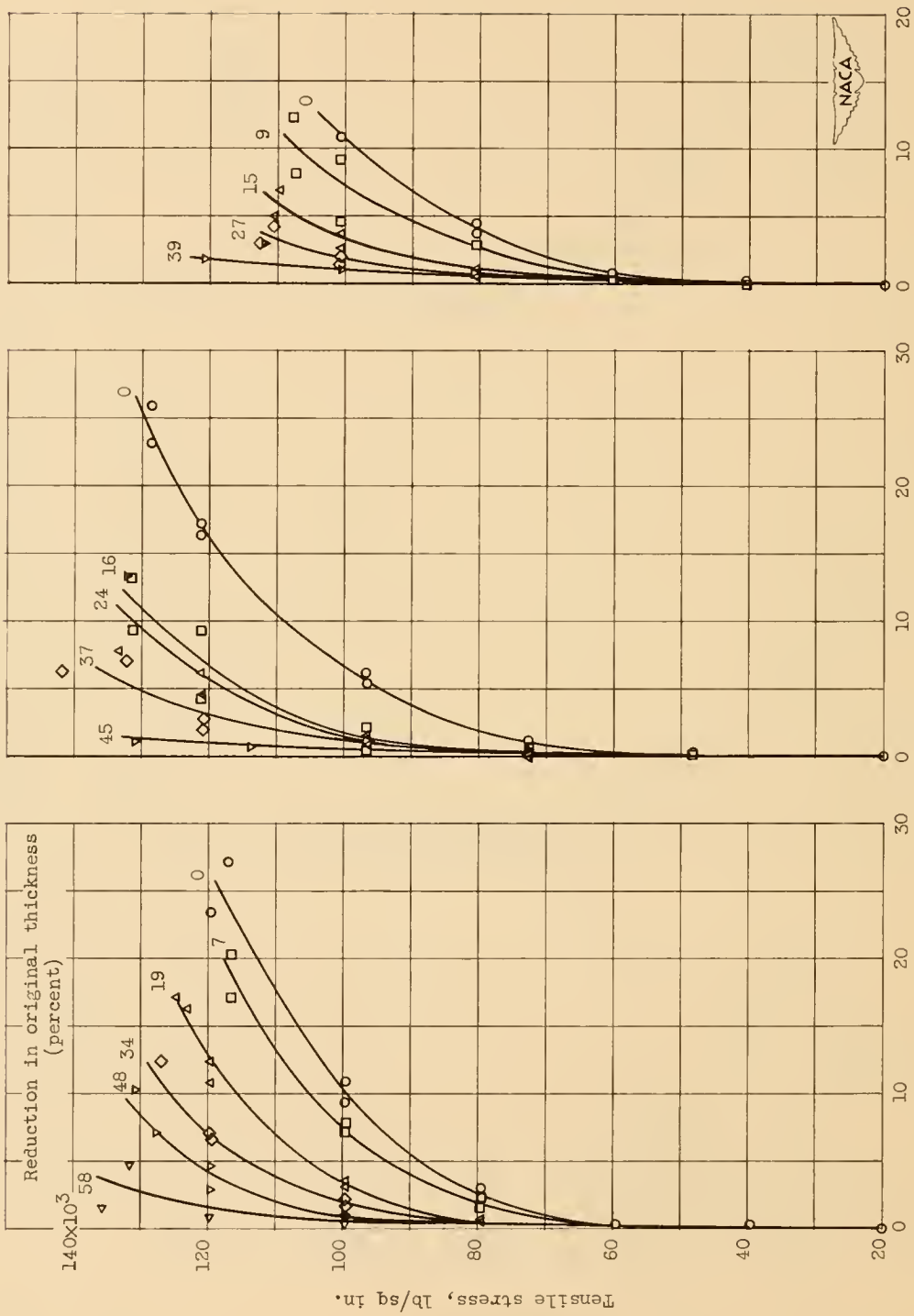


Figure 12. - Effect of cold-rolling on AISI 302 stainless steel (reference 5).



(a) Mesh, 20X250. (b) Mesh, 20X350. (c) Mesh, 28X500.

Figure 13. - Elongation of three mesh sizes of unbrazed and rolled stainless-steel corduroy wire cloth under tensile load.



(a) Mesh, 20X250. (b) Mesh, 20X350. (c) Mesh, 28X500.

Figure 14. - Elongation of three mesh sizes of brazed and rolled stainless-steel corduroy wire cloth under tensile load.

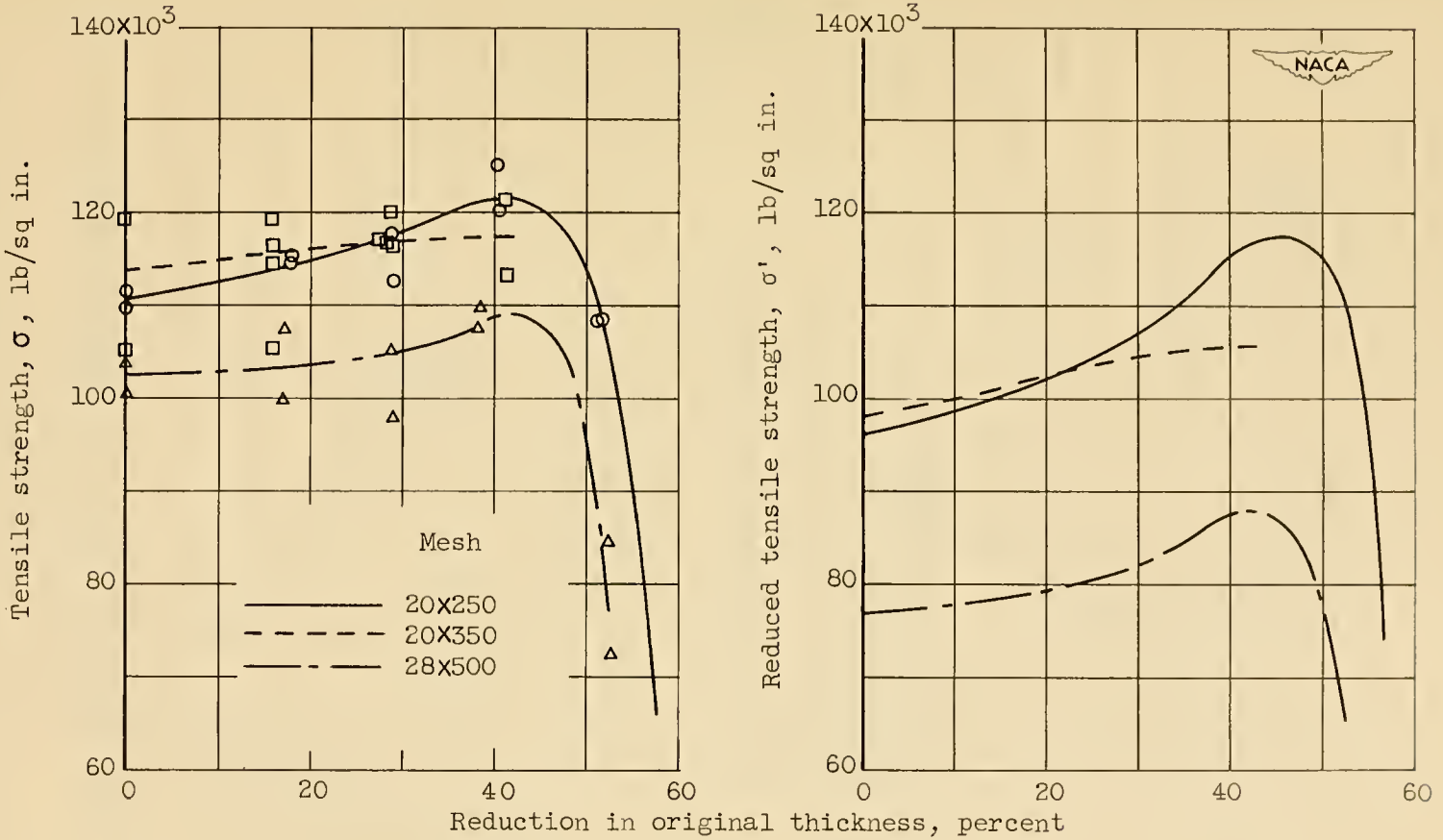


Figure 15. - Effect of rolling on tensile strength of unbrazed stainless-steel corduroy wire cloth.

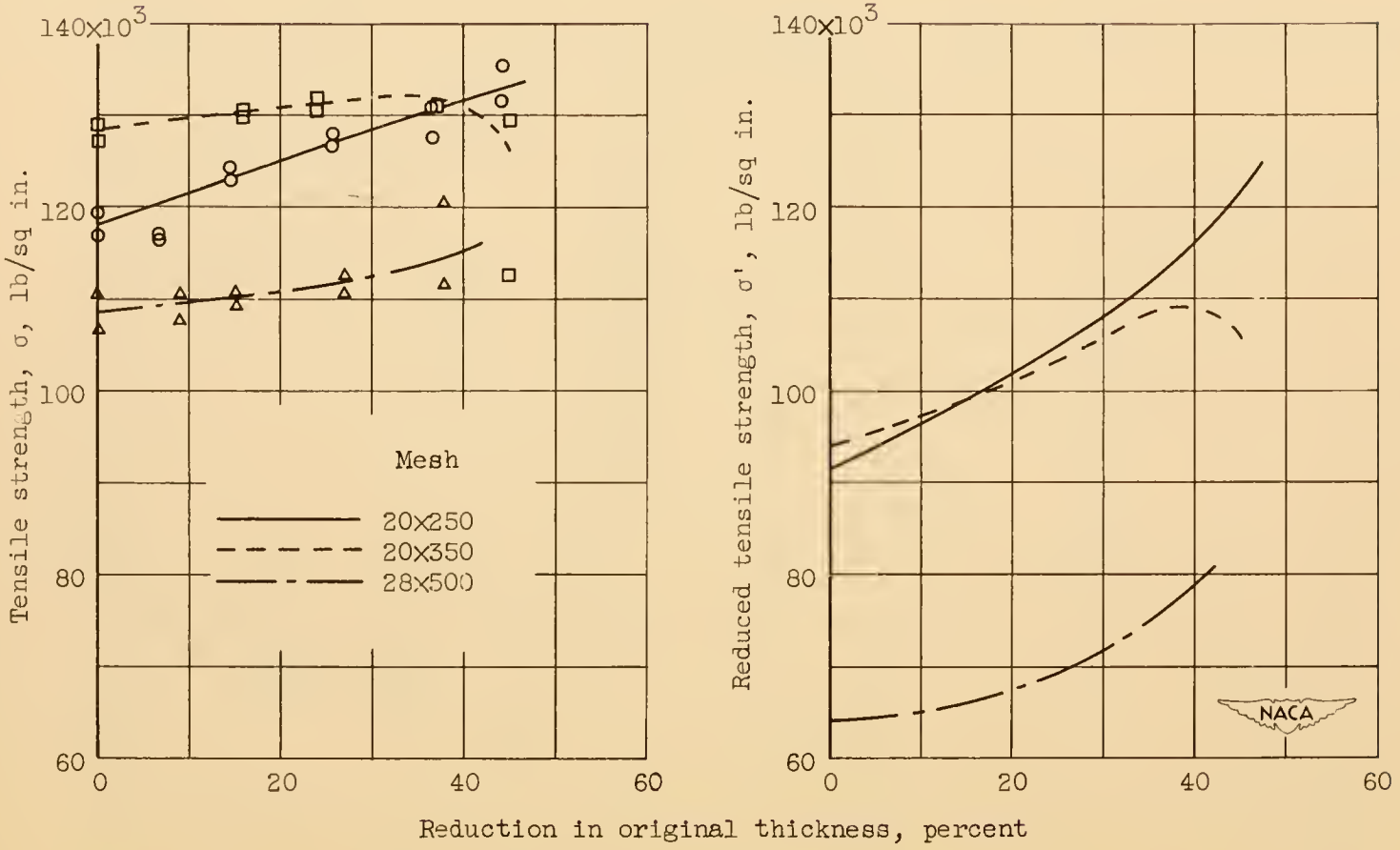


Figure 16. - Effect of rolling on tensile strength of brazed stainless-steel corduroy wire cloth.

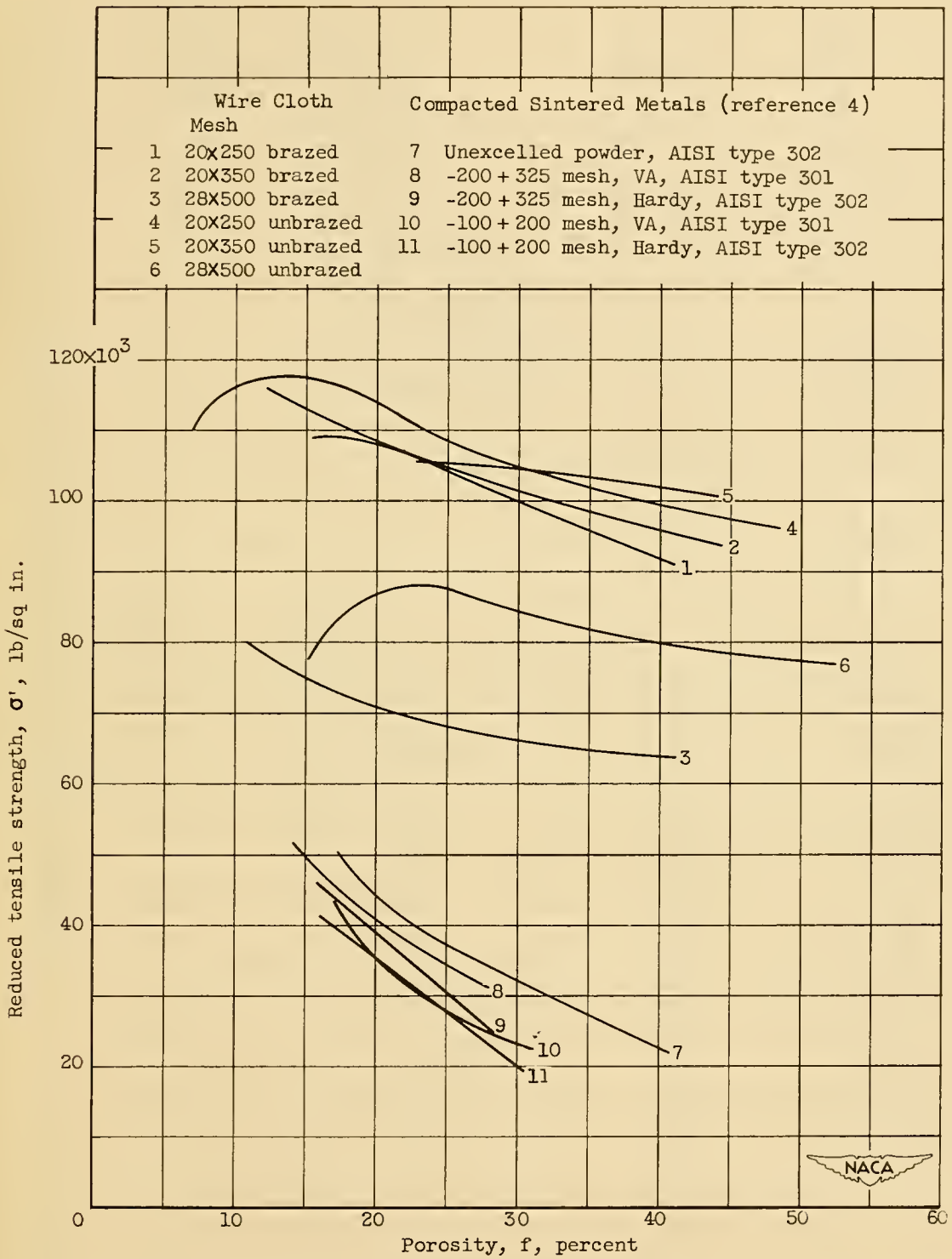


Figure 17. - Comparison of reduced tensile strength and porosity for brazed and unbrazed rolled stainless-steel corduroy wire cloth and some compacted sintered metals.

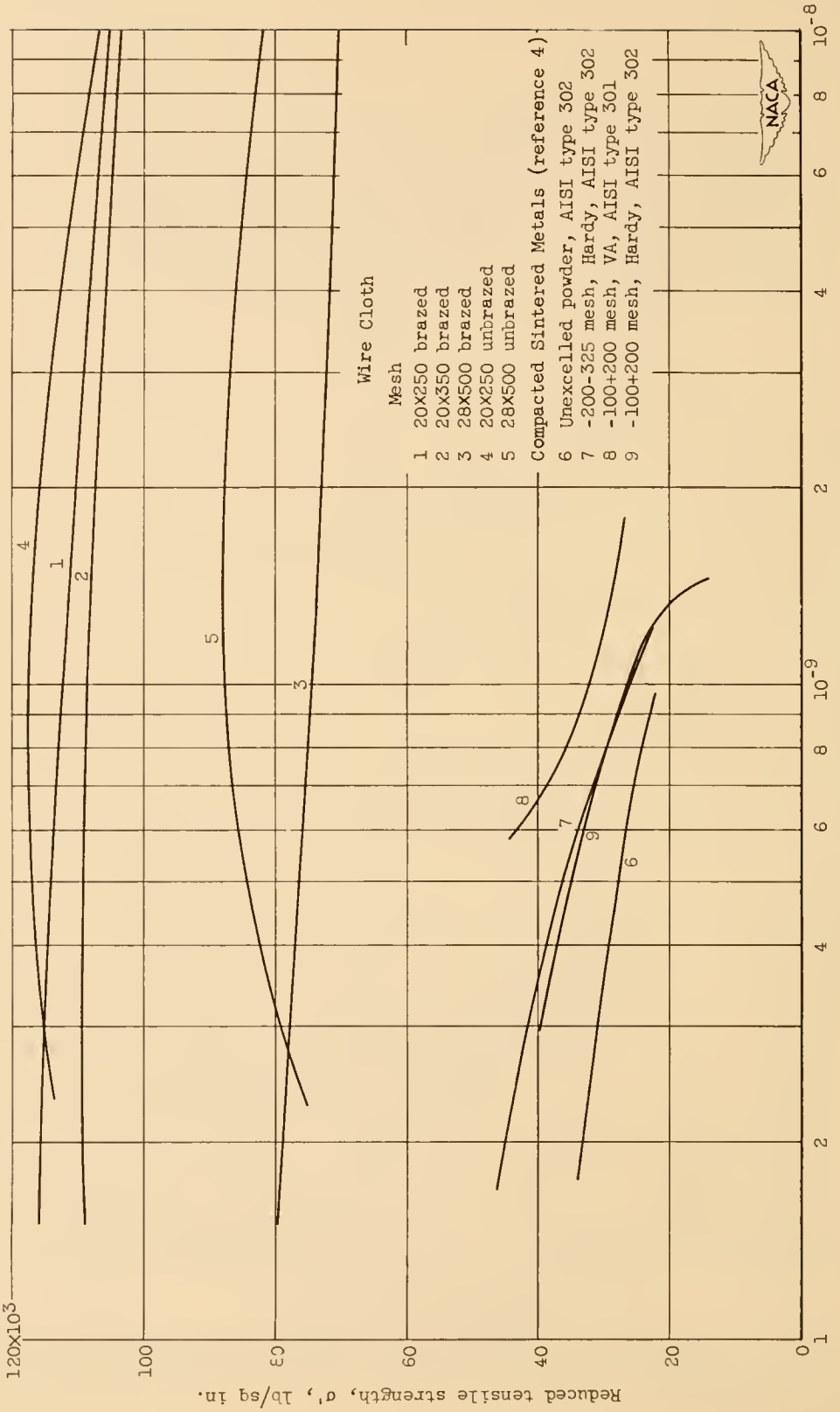


Figure 18. - Comparison of reduced tensile strength and permeability coefficient for brazed and unbrazed rolled stainless-steel corduroy wire cloth and some compacted sintered metals.

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4. Engines, Cooling (3.10)
5. Cooling - Gas Turbine Systems (3.10.2)
6. Cooling - Ram Jets (3.10.3)
7. Materials - Types (5.1)

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II. Kinsler, Martin R.
III. Cochran, Reeves P.
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